Process Safety and Environmental Protection 150 (2021) 416–432

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Pandemic risk management using engineering safety principles

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A R T I C L E I N F O

Article history:
Received 13 January 2021
Received in revised form 6 April 2021
Accepted 10 April 2021
Available online 15 April 2021

Keywords:
Risk analysis
Pandemic
Non-pharmaceutical interventions
Precautionary principle
ALARP
COVID-19

A B S T R A C T

The containment of infectious diseases is challenging due to complex transmutation in the biological system, intricate global interactions, intense mobility, and multiple transmission modes. An emergent disease has the potential to turn into a pandemic impacting millions of people with loss of life, mental health, and severe economic impairment. Multifarious approaches to risk management have been explored for combating an epidemic spread. This work presents the implementation of engineering safety principles to pandemic risk management. We have assessed the pandemic risk using Paté-Cornell's six levels of uncertainty. The susceptible, exposed, infected, quarantined, recovered, deceased (SEIQRD), an advanced mechanistic model, along with the Monte Carlo simulation, has been used to estimate the fatality risk. The risk minimization strategies have been categorized into hierarchical safety measures. We have developed an event tree model of pandemic risk management for distinct risk-reducing strategies realized due to natural evolution, government interventions, societal responses, and individual practices. The roles of distinct interventions have also been investigated for an infected individual's survivability with the existing healthcare facilities. We have studied the Corona Virus Disease of 2019 (COVID-19) for pandemic risk management using the proposed framework. The results highlight effectiveness of the proposed strategies in containing a pandemic.

1. Introduction

The global pandemic of coronavirus disease (COVID-19) is affecting billions of people worldwide with public health, livelihood, food security, fear and sufferings. Mortality, compromised mental health, and employment loss are its immediate impacts; the pandemic's long-term repercussions will be a crisis in public finance, including debt and fiscal rebalancing. The pandemic has caused more than 120 million infected cases and over 2.5 million mortalities to date (Worldometers). The World Bank's economic forecast indicates that the pandemic could dramatically reduce the gross domestic product (GDP) worldwide (World Bank, 2020). The COVID-19′s social and economic disruption is devastating; almost half of the global workforce is at risk of loss of livelihoods, tens of millions of people are in danger of falling into extreme poverty, and millions of enterprises are facing an existential threat (Joint statement by ILO, FAP, and WHO, October 13, 2020).

Vaccination is a proven method for adequate protection: however, the development, production and distribution of a vaccine requires several months. For instance, the dosage administered till date (March 2021) for the COVID-19 pandemic can meet only 3.1 % of the global population (Bloomberg, 2021) Many non-pharmaceutical interventions (NPIs) have been effective in controlling the spread of a pandemic to an acceptable level. Isolation, social distancing, putting on personal protective equipment (PPE), and following good hygiene practices, e.g., frequent hand washing and refraining from face touching, are key non-pharmaceutical strategies for containing the epidemic spread (Ferguson et al., 2020; Davies et al., 2020). Government interventions such as lockdown, school and business closures, and a ban on social gatherings are other effective measures for reducing the disease spread. The early detection of the infected cases, contact tracing, and quarantine of exposed cases are effective strategies for restricting the spread of a pandemic. The time frame of implementing and relaxing interventions also plays a vital role in controlling the epidemic. However, these preventive measures also have unwanted socio economic consequences including loss of income, poor mental health, and domestic violence. Therefore, there is a crucial need for balancing of risk and benefits.

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https://doi.org/10.1016/j.psep.2021.04.014
0957-5820/

Table 1
The constituents of a high and low level of uncertainty.

Low Uncertainty	High Uncertainty
1 Highly reasonable assumptions	1 Strong and overly simplified assumptions
2 Reliable data	2 Unreliable data
3 Consensus among experts	3 Lack of consensus among experts
4 Well understood phenomena	4 Obscure phenomena

Risk assessment is crucial in many disciplines, e.g., engineering and infrastructure, exposure assessment, process safety, occupational health and safety, risk policy and legislation, and security and defense (Aven, 2016). Risk assessment guides decision-making in selecting alternatives, approving practices, and implementing risk-reducing measures. Several risk analyses techniques, e.g. failure mode and effects analysis (FMEA), hazard and operability study (HAZOP), fault tree analysis (FTA), event tree analysis (ETA), bow-tie analysis (BTA), Markov chain analysis (MCA), and Bayesian networks (BNs) have been used for risk assessment (Cameron et al., 2017; Cui et al., 2010; Khakzad et al., 2013; Khan et al., 2015; Zhang et al., 2018; He et al., 2018). FTA and ETA are two well-established risk assessment methods for providing qualitative analysis of hazards identification and quantitative assessment of likelihood. B̈ow-tiec̈ombines the FTA and ETA by a common top-event named as a critical event (Khakzad et al., 2013; Xin et al., 2019). The layer of protection analysis (LOPA) and inherently safer design (ISD) are the other promising risk assessment and management tools. Public awareness profoundly affects public policy development for risk management (Pike et al., 2020). Renn (1998) proposed a public participation model based on integrating analytic knowledge and risk perception. Decision analysis tools such as cost-benefit analysis, cost-effectiveness analysis, and multi-attribute analysis are helpful in evaluating relative risk in the risk assessment (Aven, 2016; Kabyl et al., 2020).

Uncertainty is critical in risk conceptualization and risk assessments. Uncertainties can be categorized as aleatory (come from the variability in population/ data) and epistemic (arises from lack of knowledge of the phenomena) (Aven, 2016; He et al., 2018). Paté-Cornell (1996) proposed six treatment levels of both aleatory and epistemic types of uncertainty for risk analyses. Spiegelhalter and Riesch (2011) categorized uncertainty into five levels: event, parameter, model, acknowledged, and unknown inadequacies. The adaptive risk management approach to estimate high uncertainties was conferred by Cox (2012). The elements of the high and low levels of uncertainty have been displayed in Table 1 (Goerlandt and Reniers, 2016).

In order to deal with the uncertainities, the cautionary/precautionary techniques, also referred to as strategies of robustness, have been universally applied for minimizing risk in many disciplines (Aven, 2016). These principles are based on the development of substitutes, redundancy in designing safety devices, and safety factors. The ALARP (As Low as Reasonably Practicable) principle is a risk-reduction principle based on both risk-informed and cautionary/precautionary thinking. The ALARP principle is a fundamental approach to assessing tolerable risk. The approach sets an upper limit above which the risk must be reduced, or the activity must stop, and a lower limit below which resources expended produces negligible risk reduction (Pike et al., 2020).

Dynamic behavior of a process system and an epidemic has many similarities. Compartmental models have been employed to model the dynamics of many chemical processing systems, e.g., the Fischer-Tropsch synthesis (FTS) (Iliuta et al., 2007), bioprocess design (Cui et al., 1996; Vrábel et al., 1999), crystallization (Bermingham et al., 1998), precipitation (Zhao et al., 2017) as well as, waste treatment (Alvarado et al., 2012). Alauddin et al. (2020) presented the similarities between the SIR epidemiological model and the reaction kinetics model of a CSTR. They demonstrated resemblance in the conservation principles and distinct factors governing the contagion and reaction rates.

The methodologies to prevent, control, and mitigate infection are analogous to the hazard control and safety frameworks used in the process industries. Different safety barriers such as basic process control, alarms and operator interventions, safety instrumented systems, relief devices, and physical containments are used as control layers for the abnormal situation management of chemical processes (Dowell, 1999). Rayner Brown et al. (2021) classified the distinct measures of restraining epidemic diseases into hierarchical process safety principles. Lindhout and Reniers (2020) proposed an integrated pandemics barrier model based on sequential steps of an outbreak. They described what could have been done better in preventing and repressing the Covid-19 pandemic from a safety management perspective. Alauddin et al. (2020) developed a layer of protection analysis (LOPA) for preventive, controlling, and mitigating strategies for pandemic risk. Also, several areas of similarities were identified where process safety and epidemiology could benefit from each other. These include: (i) early fault detection vs early case detection, (ii) identification of effective control mechanism, (iii) the fast response of public health vs operator response, (iv) effective resource allocation and mobilization, (v) identification of the most vulnerable elements, and (vi) application of expertise from similar outbreaks in the past vs use of historical process data.

Engineering safety protocols are applicable to pandemic risk management to a great extent. The present pandemic also offers many learning opportunities to improve engineering risk management practices. By drawing a parallel between two domains, we believe that the lessons learned from the COVID-19 pandemic would immensely benefit engineering safety personnel and healthcare experts in efficient policymaking.

The objective of this work is to apply some of the techniques used in process safety analysis and risk mitigation in the pandemic risk management. Specifically, we have focused on applying the precautionary and ALARP approaches for evaluating the risk of infectious diseases. The contribution of this paper includes:

i *Pandemic risk analysis using the precautionary principle:* We have analyzed the risk of COVID-19 using Paté-Cornell's six levels of qualitative and quantitative analysis. The SEIQRD pandemic model and the Monte Carlo simulation have been used for risk estimation.
ii *Development of event tree diagram for pandemic risk management:* Many Risk-reducing strategies realized due to natural evolution, government interventions, and individual practices have been presented as barriers to minimize the pandemic risk.
iii *Risk analysis using ALARP:* The enforcement of risk-reducing measures, including no measure, has been studied using the ALARP approach to risk assessment. We have assessed the quantitative risk estimated using the SEIQRD model. The uncertainty in the parameters has been accounted by the Monte Carlo simulation.
iv *Survival analysis in COVID-19 with the existing healthcare systems:* The existing healthcare system's sufficiency depends upon the effectiveness of the strategies for restraining a pandemic. The survival analysis of an infected individual due to the availability of treatment under the current healthcare system has been analyzed under different strategies.

The remainder of this paper is organized as follows. Section 2 provides the mathematical model for the epidemic spread, including the risk management approaches. We have presented the SEIQRD model, followed by a brief discussion on the Precautionary and the ALARP approaches. The risk assessment of COVID-19

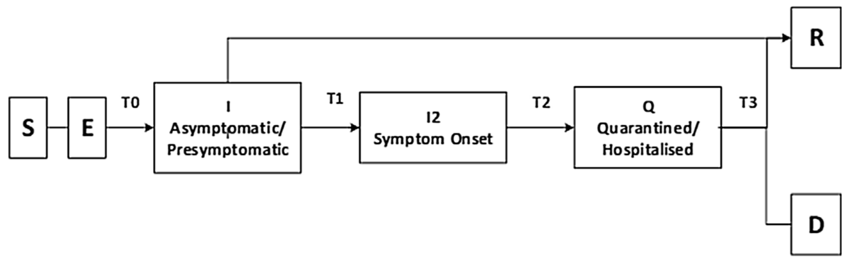

Fig. 1. Schematic representation of the SEIQRD model for infectious disease transmission (T_0: incubation period T_1: infection period, T_2: duration between case detection and quarantined/hospitalization, T_3: recovery period).

for distinct scenarios is presented in Section 3. Finally, Section 4 concludes with findings, limitations, and scopes for future work.

2. Methods and models

2.1. The SEIRQD model

Compartmental models have been widely used for the prediction and control of pandemics. They are based on systems of ordinary differential equations that focus on the dynamic progression of a population through different epidemiological states (Chowell, 2017). The population is divided into distinct compartments, each having the same state of the epidemic. The SIR (susceptible, infected, recovered) model suggests that the infected hosts become contagious immediately after exposure to an infected carrier (Anderson and May, 1979; Hethcote, 1976; Hiorns and MacDonald, 1982; Kermack and McKendrick, 1927). The latency period, the period between exposures and infectious, is taken into account by SEIR (susceptible, exposed, infected, recovered) model. Many extended compartment models have been developed to take into account isolation, quarantine, and hospitalization (Alauddin et al., 2020; Giordano et al., 2020; Hu et al., 2020; Li et al., 2020; Lin et al., 2020; Paiva et al., 2020). The SEIQRD (susceptible, exposed, infectious, quarantined or hospitalized, recovered, and deceased) model captures the effect of hospitalization and quarantine on the disease spread (Fig. 1). The mathematical formulations of the SEIQRD model are presented in Eqs.1–7, where 'a', 'b', 'c', and 'e' denote the rates of contagion, incubation, infection, and recovery. 'N' represents the population of the geographical area, d: rate of hospitalization/ quarantine after being symptomatic, φ_1 : the fraction of the symptomatic infections, and φ_2 : the fraction of the quarantined/hospitalized population resulting in mortality. The details of the models could be found in (Alauddin et al., 2020; Hu et al., 2020; Li et al., 2020; Paiva et al., 2020).

$$\frac{dS}{dt} = -\frac{aS(t)I(t)}{N} \tag{1}$$

$$\frac{dE}{dt} = \frac{aS(t)I(t)}{N} - bE(t) \tag{2}$$

$$\frac{dI}{dt} = bE(t) - cI(t) \tag{3}$$

$$\frac{dI_2}{dt} = \varphi_1 cI(t) - dI_2(t) \tag{4}$$

$$\frac{dQ}{dt} = dI_2(t) - eQ(t) \tag{5}$$

$$\frac{dR}{dt} = (1-\varphi_1)cI(t) + (1-\varphi_2)eQ(t) \tag{6}$$

$$\frac{dD}{dt} = \varphi_2 eQ(t) \tag{7}$$

2.2. Engineering safety: the precautionary principle

The precautionary principle or *the precautionary approach* defines a key procedure in risk management, especially where uncertainties are difficult to quantify. It is a principle for making practical decisions under scientific uncertainty (Gollier and Treich, 2003). A precautionary decision-making approach emphasizes the implementation of prompt and effective preventative action, even in the absence of full scientific evidence of cause and effect. UNESCO's World Commission on the Ethics of Scientific Knowledge and Technology defines precautionary principles as Ẅhen human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm (COMEST, 2005)".

Sandin (1999) reviewed the various definitions of the precautionary principle along four key dimensions: threat, uncertainty, action, and command, as presented in Fig. 2. Threat refers to the nature of the imminent harm: its seriousness and irreversibility. *The precautionary principle* is about "Go slow and ask smart questions." A wide range of alternative actions, including inaction, should be examined for the severity of the potential harm along with the consideration of the moral implications.

2.3. Engineering safety: the ALARP principle

The *ALARP (as low as reasonably practicable)* approach is based on risk-informed and cautionary thinking. The ALARP principle states that risk-reducing measures should be implemented, provided that the costs are not grossly disproportionate to the benefits earned (Pike et al., 2020). This usually applies to the tolerability region, which is the region between intolerable and accepted risk levels. The risk should be reduced, or the activity must be discontinued if it exceeds the maximum tolerable level (Pike et al., 2020). All critical words in ALARP: 'low', 'reasonably', and 'practicable' are relative terms with no standardized values. The risk acceptance is a complex process influenced by several factors such as the order of risk, the extent of societal participation, and corresponding regulations and guidelines.

Fig. 3 outlines the pandemic risk assessment using Engineering Safety tools such as the PP and the ALARP. The precautionary approach has been examined to estimate the pandemic's risk with and without implementing risk-reducing measures. The enforcement of distinct risk-reducing measures, including no measure, has been evaluated using the ALARP approach. We have employed the SEIQRD model for the quantitative analysis, i.e., calculating the number of newly infected cases, hospitalization, recovered, and the mortality due to the pandemic. The randomness in the model parameters' values, e.g., incubation, infection, and recovery periods, has been captured using the Monte Carlo simulation. Finally, we have estimated the reliability of the existing healthcare facility under distinct strategies.

1. **Threat/ Harm:**
   - Can be evaluated by creating and evaluating credible scenarios.
   - The credible scenario can be analyzed using risk assessment techniques

   What to consider for the threat:

   A. Magnitude:

   Is it serious?

   What's the cumulative impact?

   Would risk assessment help with the analysis of the scenario?

   B. What Kind:

   Is it irreversible?

   Is it easily avoidable?
2. **Uncertainty:**
3. **Action**

   $$Action\ taken \propto Seriousness\ of\ the\ potential\ harm$$

   Questions to ask for action/inaction:

   Just wait, or can we use science to mitigate it?

   Can we use science to anticipate?

   What risk reduction strategies should be employed?

   Can we use science to make our system resilient towards the threat?

   Can we do something to reverse it?

   At what point take action?
4. **Command**

Fig. 2. Dimensions of Precautionary principles (Sandin, 1999).

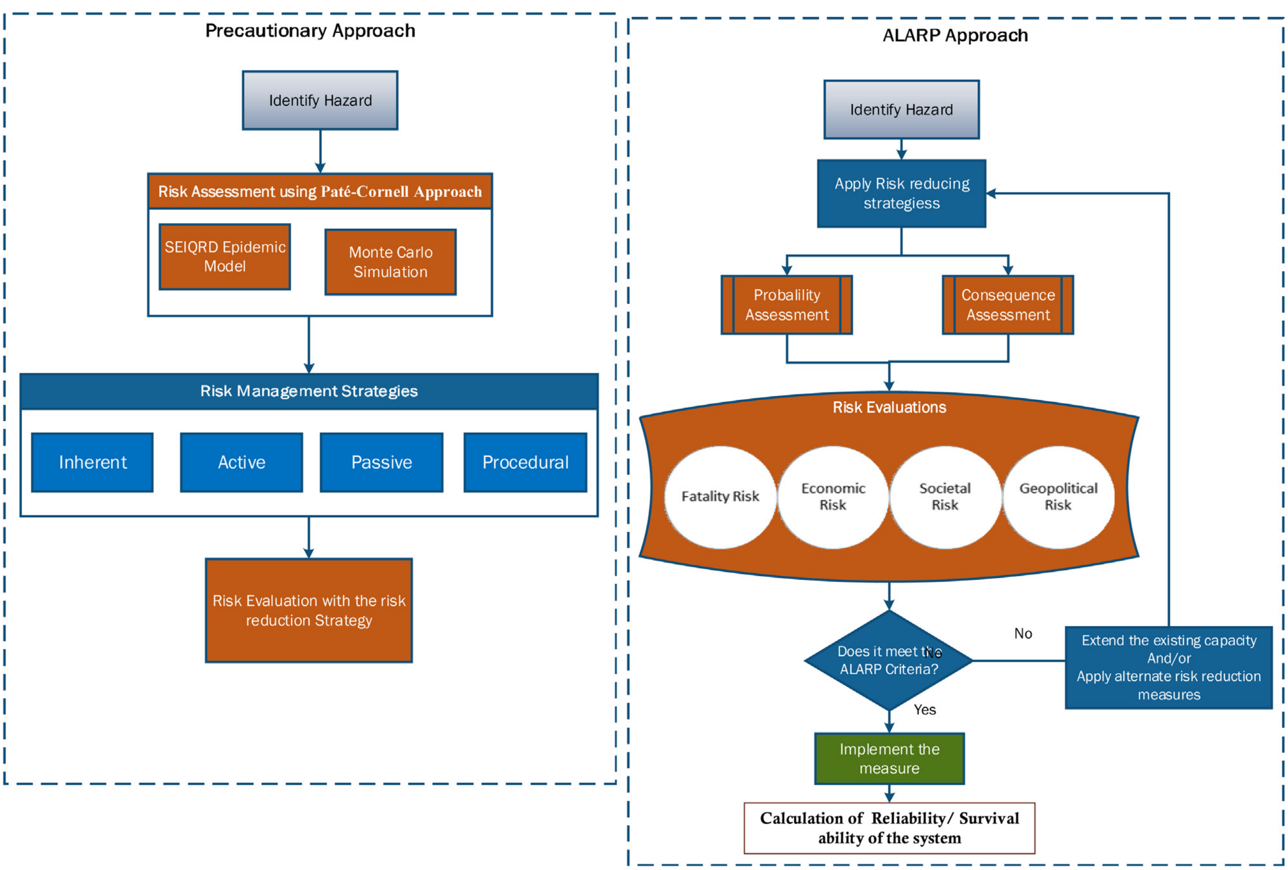

Fig. 3. Mechanistic models for pandemic risk management.

3. COVID-19 modelling using engineering safety principles

Engineering safety models have been used to study the risk management of COVID-19, a global pandemic, and severe disruption of the 21st century. The disease can lead to a range of outcomes, including no symptoms, mild illness, mental disorder, shortness of breath, sore throat, headache, myalgia, fatigue, loss of taste, fever, muscles or body aches, congestion, nausea, diarrhea, and death (CDC). The case fatality rate (CFR) of COVID-19 varies by location, the intensity of transmission, the demography, accessibility of sophisticated healthcare, and the patient's history of chronic disease. Personal hygiene (e.g., wearing a mask at public places, frequently washing hands), social distancing, and govern-

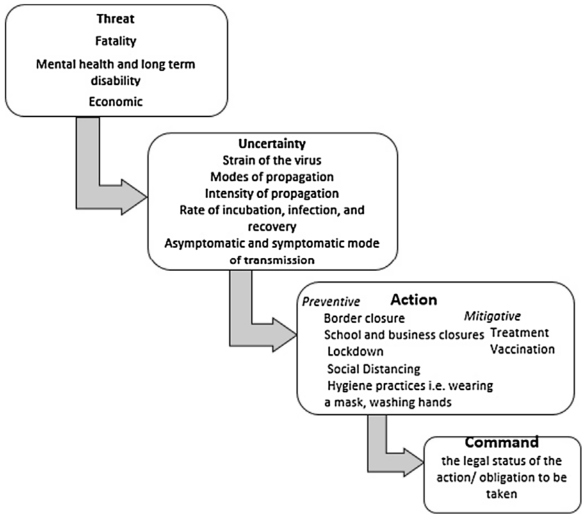

Fig. 4. Schematic representation of the precautionary principles for managing a pandemic risk.

ment interventions are critical in restraining the epidemic spread of COVID-19.

An epidemic's transmissibility is characterized by the basic reproduction number (R_0), which is defined as the average number of secondary cases generated by a primary case in an entirely susceptible population (Ferguson et al., 2005). The epidemic spreads for R_0 >1 and dies out if R_0 <1. The basic reproduction number for the COVID-19 reported by the multiple sources varies from 1.5 to 5.0. We have used R0 = 2.9, the median value reported in (Liu et al., 2020, and Alauddin et al., 2020). The average values of the incubation, infection, and recovery periods have been assigned to 5.5, 5.1, and 11.5 days, respectively.

We have studied the risk management of COVID-19 for Ontario, the most populous province of Canada, with 14.6 million people representing 38.8 % of the country's population (Ministry of Finance, Government of Ontario)

3.1. Risk assessment of COVID-19 using PP and the SEIQRD model

The precautionary principle is fundamental in suppressing a pandemic. Fig. 4 presents the outline of the precautionary principles for managing the present pandemic. A pandemic outbreak contains many sources of uncertainties: strains of the virus, modes of propagation (airborne or contact transmission), the intensity of propagation (uncertainty in the R-value), rate of incubation, infection, and recovery, number of total infections, and the existence or non-existence of asymptomatic spreading. According to the precautionary principle, firm decisions need to be made to protect health in such uncertainties. The geographical region lockdown until the evidence of diminishing the disease's spread is the ultimate precautionary measure for reducing the pandemic risk. However, it incurs severe socio-economic consequences. We have estimated the pandemic risk using the SEIQRD model under the precautionary approach.

3.1.1. Quantitative risk assessment of COVID-19

Risk assessment can be expressed in terms of answering three questions; what can go wrong, how likely is it, and what are the losses or consequences? Paté-Cornell (1996) proposed six modes of treatment of both aleatory and epistemic types of uncertainty for risk analyses. Mode 0 is about hazard identification or multiple ways of failure of the system. Mode 1, the worst-case approach, is based on the accumulation of worst-case assumptions and provides the maximum loss. No notion of probability is taken into account in this mode. Mode 2, the quasi-worst case scenario, deals with evaluating the worst possible conditions that can be reasonably expected. Mode 3 is based on a central value, e.g., the mean, the median, or the mode of the outcome. Mode 4 is based on the probabilistic risk analysis (PRA) approaches. Mode 5 displays uncertainties about fundamental hypotheses by a family of curves. Bayesian and Monte Carlo estimations are included in the tools for probabilistic risk calculation at modes 4 and 5. We have employed the SEIQRD model for the quantitative risk estimation of the COVID-19 pandemic. The Monte Carlo simulation has been used for handling the randomness in the values of the model parameters, e.g., incubation, infection, and recovery periods.

The number of daily infected cases of COVID-19 corresponding to Mode 1, 2, and 3 have been presented in Fig. 5. The expected and the 95 percentile values of the newly infected cases are 3.1 $\times$ 10^4 and 4.8 $\times$ 10^4, respectively. This number of daily cases could reach 7.5 $\times$ 10^4 in the worst-case scenario. Fig. 6 presents the risk considering the probability, and pandemic impact corresponds to Mode 5 of the Paté-Cornell (1996). Here, the dotted line presents the impact of the pandemic in terms of the expected values of the newly infected cases, while the solid line denotes the risk defined by the product of the impact of the pandemic and the probability of the occurrence of the impact. The probability of the occurrence of the infection has been computed using the Monte Carlo simulation of the distribution of the infections considering the randomness of the model parameters (i.e., the incubation period, infection period, and recovery period). We can also observe that the nature of the distribution depends on the relative maturity of the outbreak. Fig. 7 illustrates the uncertainty in the analysis. The shaded region denotes the area between 95 and 5 percentile values of the new cases of COVID-19.

The aforementioned analyses are based on the SEIQRD pandemic model of the risk calculations. The analyses assume no measures were taken to restrain the spread. However, the risk is reasonably minimized by implementing distinct risk reduction strategies, as discussed in the next section.

3.1.2. Risk-reducing strategies of COVID-19

Following the engineering risk reduction classifications (Crowl and Louvar, 2011), the risk reduction activities for COVID-19 could be classified into four categories: inherent, active, passive, and procedural, as shown in Table 2. It also categorizes distinct risk-reducing measures in pre-pandemic and during pandemic. Inherent strategies identify and implement ways to eliminate or significantly reduce the hazard.They are described by four actions: minimization; substitution; moderation; and simplification. Although inherent strategies perform well when considered early in the life cycle of industrial activity, they can be applied at any stage to reduce the risk of existing activities (Amyotte et al., 2018).

Birds and animals act as a source, reservoir, and carrier for most infectious diseases. A study reveals that 62 % of all human pathogens are classified as zoonoses (Vorou et al., 2007). Bats are notorious primary sources of pandemic-causing viruses such as MERS (Middle East Respiratory Syndrome), SARS (Severe Acute Respiratory Syndrome), and Nipah. A pandemic could be prevented by avoiding the interaction and handling of birds and animals. However, it is impractical as many people interact with them for food, fibre, livelihoods, transport, sport, companionship, and education. They can also be infectious via other transmission media, e.g., air, water, and soil, even if we avert direct contact. Another inherent strategy for preventing a pandemic is by avoiding human-to-human interactions. This is possible by changing the operational formats such as activating home delivery services, working from home, and switching to teleconferencing and virtual modes of oper-

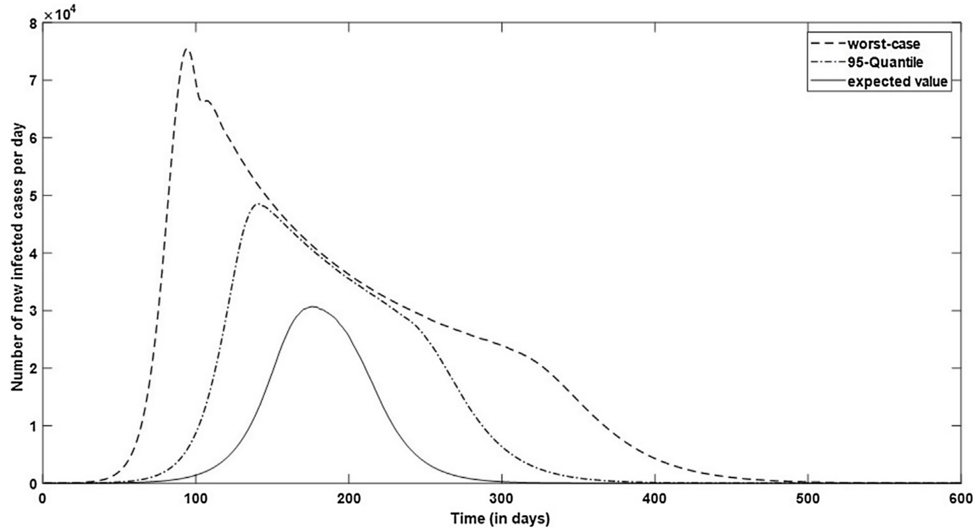

Fig. 5. Infection cases (Mode 1, 2, and 3) due to COVID-19 pandemic if no measures have taken.

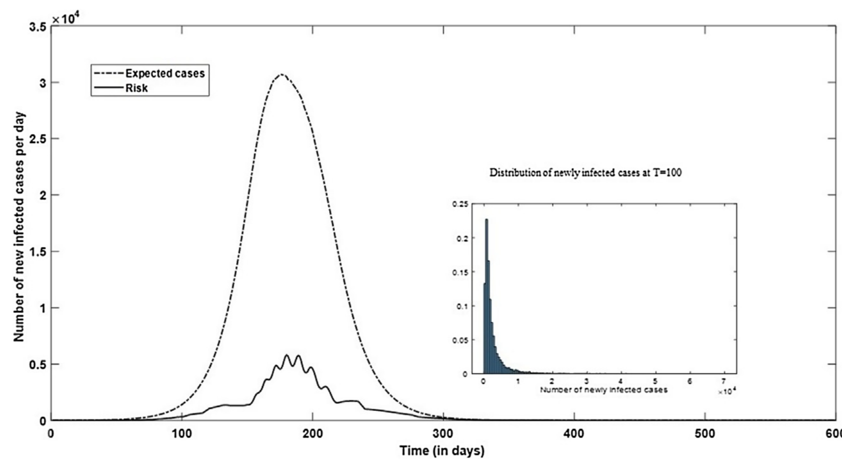

Fig. 6. Risk of infection (Mode 4) due to COVID-19 pandemic if no measures taken.

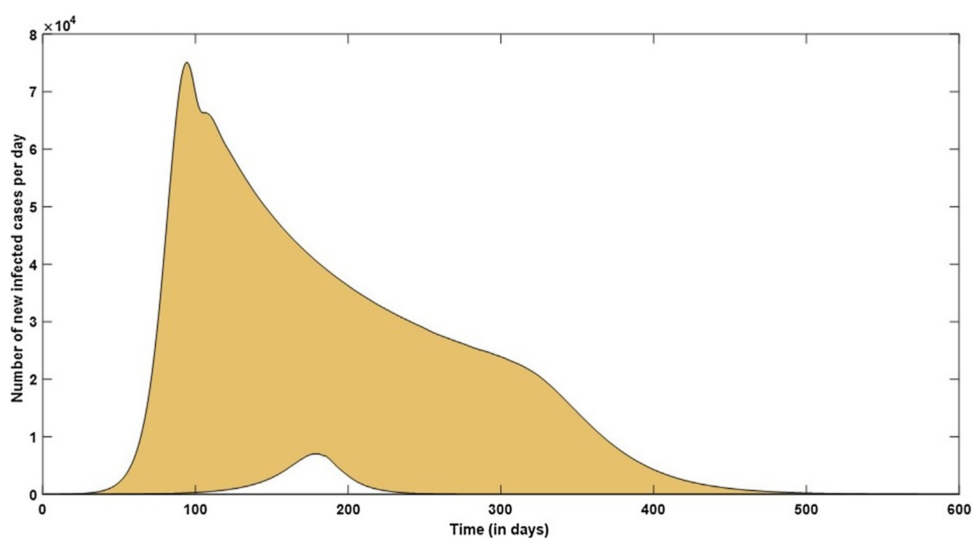

Fig. 7. Uncertainty in the fatality risk (Mode 5) due to COVID-19 pandemic if no measures taken.

Table 2
Categorization of risk-reducing strategies for COVID-19 pandemic.

Type of measures/ barriers	Stage and risk reduction strategies	Type of risk reduction strategies	Nature and implementation of the risk reduction strategy	Remarks
Preventive	**Pre-pandemic** • Avoid direct contact/ interaction/ handling animals	*Inherent*	–	Extremely difficult to implement. Many known mammals play a vital role in human life but act as potential virus sources and/or carriers. For instance, MARBURG 1967 (bat) EBOLA 1976 (bat) SARS 2002 (bat) SARS 2012- (bat) SARS-CoV-2 2019 (presuming bat) MERS 2010 - (Camels) H5N1 (Bird flue) 2003- (Chicken) H7N9 (Bird flue) 2013- (Chicken)
	During-pandemic: • Avoid physical interaction with others • Activate work from home strategy and home delivery services	*Inherent*	Administrative recommendation that requires to be practiced by individuals and organizations	Effective mechanisms to prevent a pandemic. However, all individuals and operations cannot go online. Besides, there is a possibility of defaulters depending upon the level of administrative action (recommendation, requirement, and its enforcement)
	During Pandemic: • Enforcing lockdown • School and business closures • Restricting large gatherings • Frequent hand washing/sanitizing/ refrain from face touching	*Active*	Administrative recommendation that requires to be practiced at individual and community level	Effective mechanism in minimizing the pandemic impacts. However, it is challenging to enforce and monitor enforcement. They incur significant economic loss
	• Social distancing Avoiding crowded places/ public transport	*Inherent*		
	During Pandemic: • Vaccination	*Inherent*	Administrative recommendation that requires to be followed by individuals	The most effective strategy. It provides the fastest way to minimize the pandemic impact provided Vaccine is available and accessible to all.
	During Pandemic: • Redesign/installation of safety layers at the interactive systems, e.g., shield at cash and other counters	*Passive*	Engineering	An effective strategy to minimize the disease spread. However, it requires proper planning and execution.
	During Pandemic: • Self-isolation • Wearing a mask/ PPE • Good Hygiene practices • Surface Cleaning	*Procedural*	Administrative recommendation that requires to be practiced at individual and community level	The efficiency of the strategy is dependent on individuals to follow the best practices.
	During Pandemic: • Contact Tracing • Rapid Testing • Awareness about the situation and safe handling procedures • Peer pressure and police intervention for following procedures • Special attention and guidelines for the vulnerable groups	*Procedural*	Administrative	It requires significant resources to enforce the measures.
	During Pandemic: • Immunity	*Passive*	Achieved through herd protection, genetics or use of diets to strengthen the immune system.	This is an effective passive strategy; however, it is highly variant depending upon the individual's immune system.
Mitigative	**During Pandemic:** • Quarantine of exposed cases • Treatment • Extending healthcare systems/ hospitals/ workers/antidotes	*Procedural*	Administrative	It requires decisions to activate the strategies effectively and mobilize the resources. Requires long-term planning The prevalent outbreak can be used to upgrade the healthcare systems to respond well in future outbreaks.

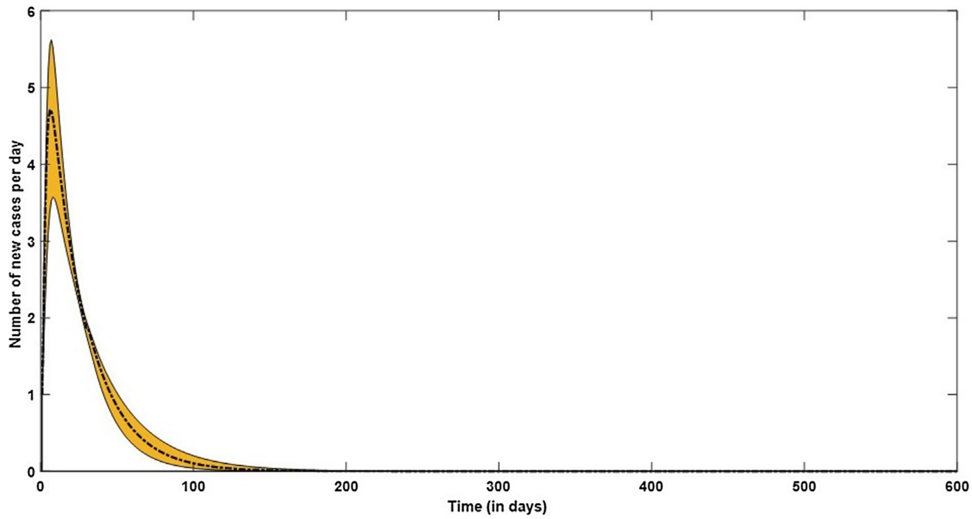

Fig. 8. New infection cases of COVID-19 pandemic under the lockdown.

ation. Nonetheless, the absolute interaction-free environment is highly unlikely to date due to two obvious reasons: (i) the virtual modes is not feasible for all activities and workplaces due to their reciprocative nature e.g., healthcare workers (ii) the requirement of a fraction of the workforce for the maintenance of the virtual environment. Many experts believe that an infectious disease outbreak could be wiped out if the world stands still for around the virus's survival time.

Lockdown, school and business closures, restricting large gatherings, following social distancing, putting on PPE, and hygiene practices such as frequent hand-washing are other common inherently safer approaches to pandemic risk management. Lockdown, school and business closures and other government regulations have other associated risks such as mental health disorders and severe economic impairments (Singh et al., 2020). These advisories entail making informed decisions on when to activate and relax various enforcements.

Contact tracing, increasing testing capacity, and quarantine of the exposed cases could be classified as administrative strategies of pandemic risk management. They are compelling in limiting the disease outbreak (Institute of Medicine (IOM), 2007). However, they must be triggered at the right time to achieve the desired outcome. A delay in detecting infected cases leads to a delay in the mitigative actions that escalate the risk. Hygiene practices such as frequent washing of hands and refrain from face-touching are other proven active measures for suppressing the disease if exposed to the Coronavirus.

Unlike active strategies that require event detection and device actuation for their functioning, passive engineering safety strategies comprise barriers that do not need activation to accomplish their intended functions. Bolstering immunity either by changing lifestyle or achieved through herd protection is an effective passive strategy for reducing the pandemic risk. The shield at cash and other counters is another example of a passive control mechanism of restraining the disease's spread. The passive strategies require long-term planning. The present outbreak can be helpful in upgrading our passive control systems for reducing the risk of future infectious diseases.

Providing sophisticated treatment to infected people is a procedural method for mitigating a pandemic risk. The existing healthcare facilities might need to be extended to meet the demands of treating a large number of infected cases. Thoughtful decisions have to be made to mobilize resources and aid preferential treatment to vulnerable groups in case of limited availability. The other effective procedural strategies include awareness about the situation, special attention and guidelines for the vulnerable groups, e.g. elderly and chronic patients, peer pressure and police intervention for following the procedure.

The categorization of the strategies into inherent, active, passive, and procedural is subjected to the study's focus. Social distancing, hygiene practices, and other enforced regulations such as lockdown, school and business closures, and restricting large gatherings are inherent risk reduction measures for a susceptible person. However, these factors could be documented as procedural measures for alleviating the pandemic risk to a community if the virus is already present in the community.

3.1.3. Risk management of COVID-19 using the risk reducing strategies

Distinct government regulations and individual responses could minimize the risk of a pandemic. Limiting gathering sizes, closure of nonessential business and schools, and emergency lockdown have a decisive role in controlling the epidemic spread. Lockdown is the most effective measure for reducing risk. However, prolonged strict lockdown can cause compromised mental health and severe economic impairment. We have modelled the lockdown as a precautionary approach. Fig. 8 demonstrates the effect of lockdown enforced after a month of the first case reported. The lockdown will reduce the peak to less than 10 new cases as opposed to 3.1×10^4 if no measures are taken. The variation of the value due to randomness is presented using the shaded area in Fig. 8. The timing of the enforcement and relaxing the lockdown is crucial in restraining the epidemic risk (Alauddin et al., 2020).

The results present the effectiveness of the lockdown (and other interventions in the forthcoming sections) in reducing infections and fatality in relative terms. The estimates were not corrected for other potential confounders' effect, for example, wearing mask, hygiene practices and following voluntary social distancing, which could have contributed to reducing the disease spread in addition to the observed interventions. Our study also does not explicitly consider the other key factors such as the scale of testing, contact tracing, and imperfections in case isolation, demographics, heterogeneities in contact patterns, and spatial effects. The results were also not adjusted for fatalities arising from the interruption in health services for chronic disease. Many surveys highlighted the partial or complete disruption of healthcare for hypertension, diabetes-related complications, cancer treatment, and cardiovascular emergencies due to the newly imposed regulations during the COVID-19 pandemic.

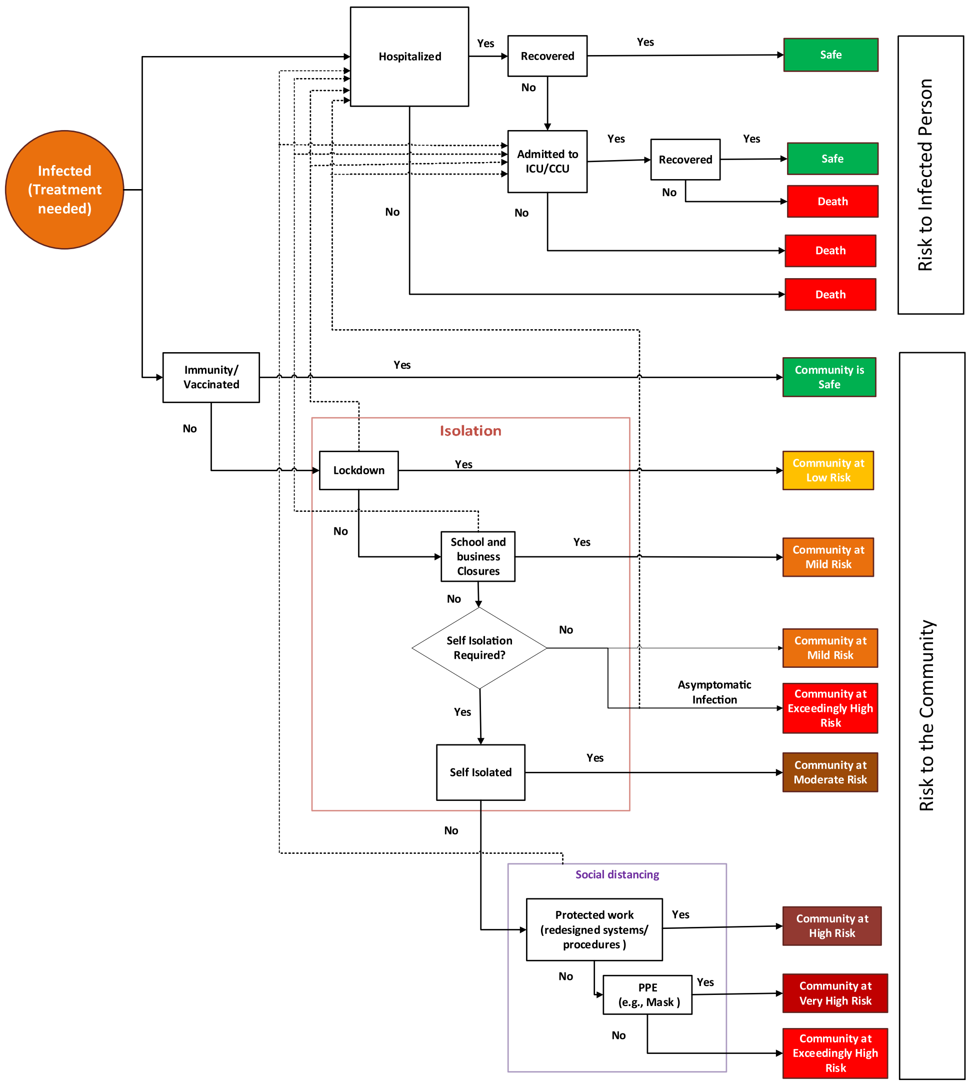

Fig. 9. Impact on the infected person and the community due to the infection.

The effectiveness of these measures depend on the context of implementation, such as the presence of other NPIs, country demographics, the economic status, degree of compliance of the population and societal impact, comorbidities, overall risky environment and country vulnerability to biological threats. The same NPI could result in different outcomes in different countries, even different parts of a country. Application of expertise from similar outbreaks in the past could be conducive to the credible estimate of the trajectory and slowing down the spread (Goudarzi S, 2020, March 23). The expertise from the past outbreaks e.g., the 2003 severe acute respiratory syndrome (SARS) outbreak in Singapore, and experience with the 2015 Middle East respiratory syndrome (MERS) outbreak of South Korea led to an immediate fruitful response to the COVID-19. The economic support by emergency funding to the poor and needy populations for alleviating the financial burden is also helpful in effective closures and lockdown.

3.2. Event tree analysis of COVID-19

A pandemic can cause socio-economic damage, compromised mental health and mass mortality. Many preventive and repressive or mitigating measures have been explored to minimize the negative consequences of infectious diseases. The term 'prevention' refers to measures taken to prevent the occurrence of an unwanted event while 'repression' translates to the measures taken to mitigate the consequences of the undesired event. Repressive barriers are put in place to avert, mitigate and minimize the adverse effects of the central event (Lindhout and Reniers, 2020).

Fig. 9 depicts the impact of epidemic on an infected individual as well as on the community. The end states have been divided in two subgroups: risk to an infected person (including safe and death as the scenarios), and risk to the community with many scenarios such as safe, low risk, moderate risk, high risk, very high risk, and exceedingly high risk. Lockdown, school and business closures, self-isolation, and social distancing, significantly reduce the risk. Fig. 9 also illustrates that the asymptomatic spread could be catastrophic if not mitigated properly. A detailed analysis of the event tree and bow-tie analyses of COVID-19 for subsystems could be found in (Rayner Brown et al., 2021).

Super-spreading incidents and multiple infections from a single infected individual were the key driver of the COVID-19 transmission (Frieden and Lee, 2020). Some of those events include the Biogen meeting (Weintraub, 2020), the Caul's Funeral Home at St John's (Courage, 2020), the White House Event (BBC, 2020), the Cluster of Bars in Hong Kong (Danmeng and Jia, 2020), the Church Choir Practice in Washington (Williams, 2020), and the Nursing Homes Washington (McMichael et al., 2020). Asymptomatic and presymptomatic infections are the viruses' greatest means

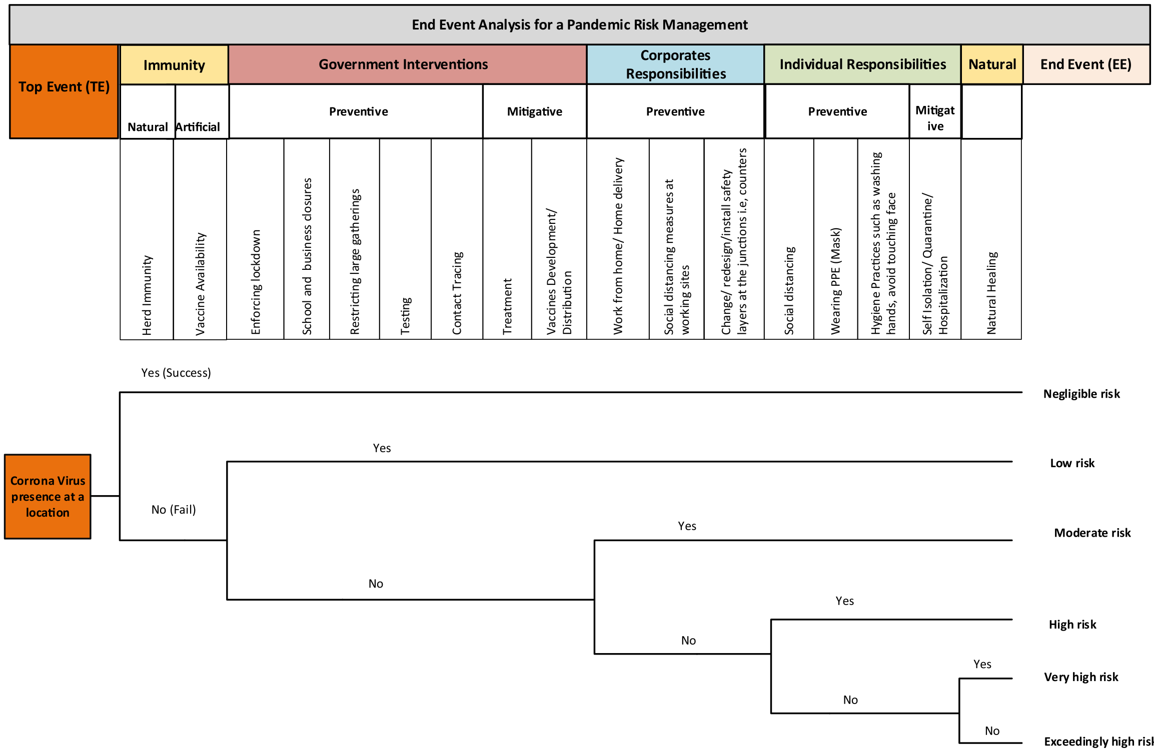

Fig. 10. Event Tree model of distinct risk reduction strategies of a pandemic.

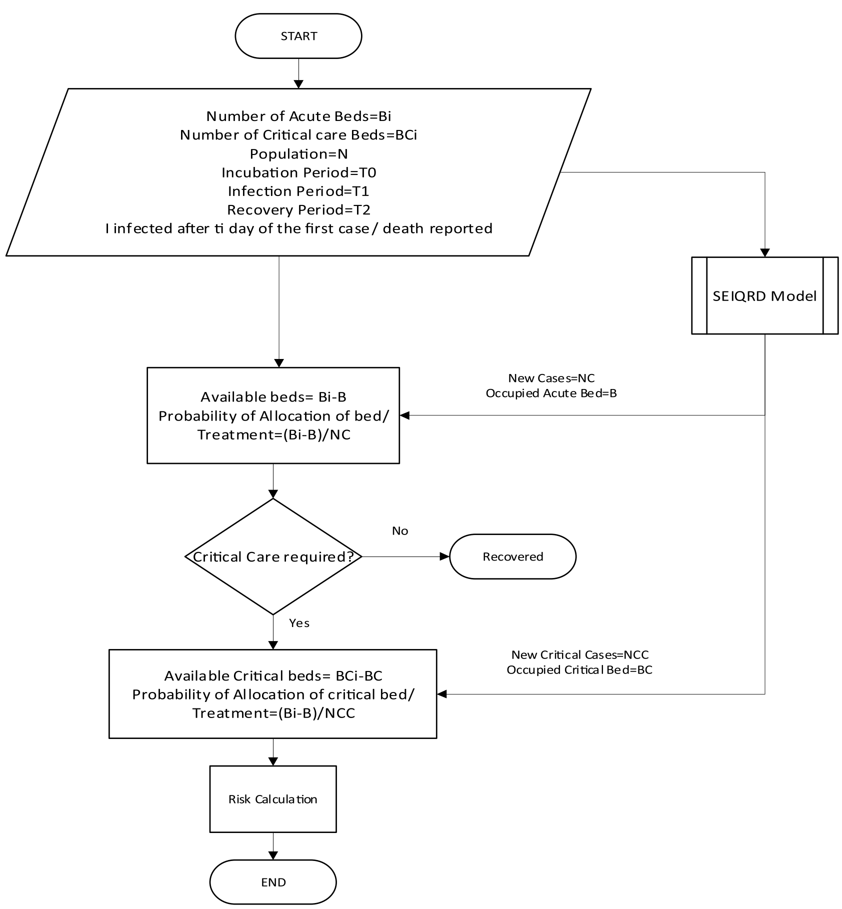

Fig. 11. The calculation of the availability of acute and critical care beds during the pandemic.

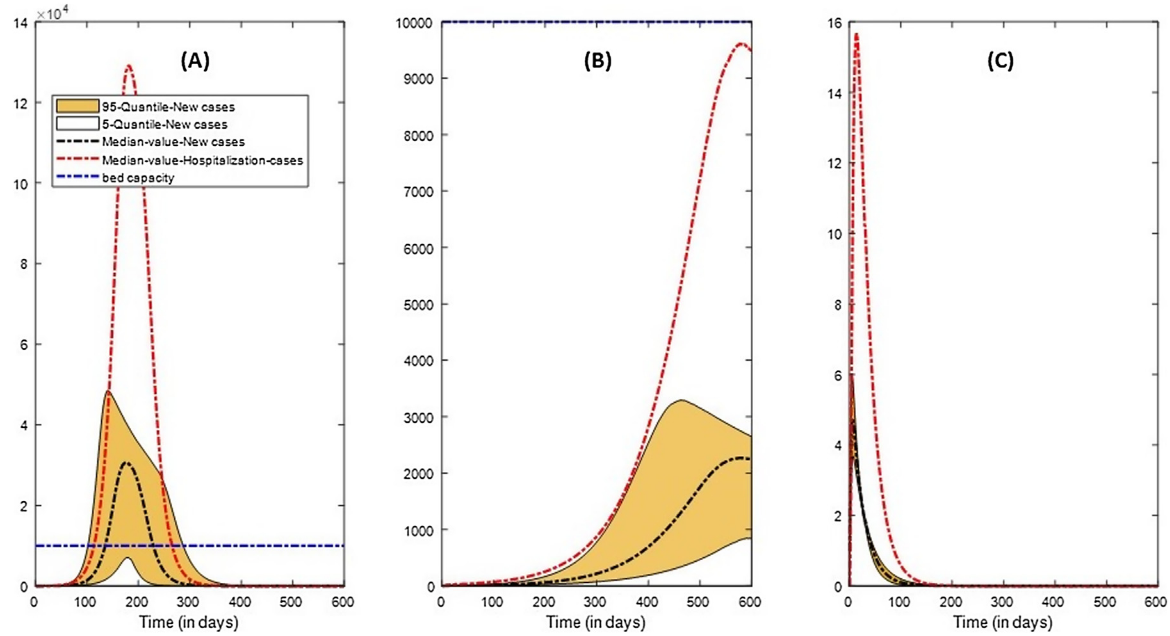

Fig. 12. The number of infected cases due to COVID-19 pandemic under distinct measures. A. No measures, B. School and business closures, C. Lockdown.

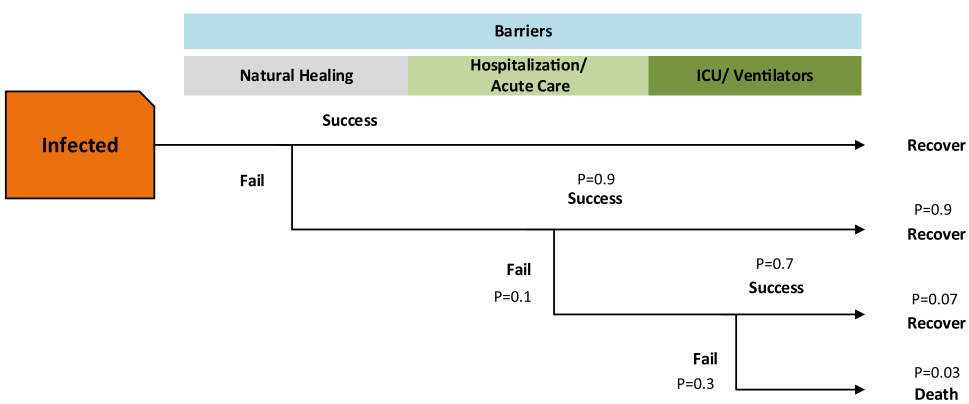

Fig. 13. Event tree analysis for risk to an infected person **at T = 200th** day of the outbreak with schools and business closures in effect.

of spreading diseases. According to a reprint (Goyal et al., 2020), almost 62 percent of super-spreading COVID-19 occurred through the presymptomatic transmission. The interventions such as lockdown, school and business closures, and limiting gatherings are central in preventing super-spreading events.

Lindhout and Reniers (2020) presents a risk management framework considering the root cause to the long-term effects of a pandemic outbreak. Many studies proposed temporal and spatial segregation measures to restrain a pandemic. Government interventions such as school and workplace closures, stay-at-home orders and a ban on large gatherings will cause a community-wide contact rate reduction. However, these interventions can not be imposed for a longer duration due to high incurred cost and other associated risk. Individual practices and societal responses are central to the effectiveness of these measures. Self-imposed measures such wearing a mask at public places, voluntary social distancing, and handwashing are vital in in preventing the subsequent waves of an outbreak.

An event tree presents the known consequences of an abnormal event. Fig. 10 shows the Event Tree model of distinct risk reduction strategies of a pandemic. The risk will be negligible if immunity is achieved either through natural, i.e., herd immunity or vaccination. However, it takes several months following the outbreak. Government interventions such as lockdown, school and business closures, restricting large gatherings, and extending healthcare systems help in restraining a pandemic. Corporates and employers can assist in controlling the risk by transforming operational formats, such as enabling home delivery services, working from home, and switching to a virtual mode for meetings. The individual responses: following social distancing, wearing a mask, and hygiene practices efficiently repress a pandemic's spread.

The efficacy of all barriers is not alike; some are more prone to failure due to their distinct nature, porosity, constraints, and degradation characteristics. For example, the individualistic-based measures, e.g. social distancing, washing hands, could be weakened due to people's complacent nature, especially if the outbreak persists for a longer duration. Likewise, the lockdown cannot be imposed for a prolonged time due to its severe economic consequences. The measures are interactive; the effectiveness of each measure depends on the others. For instance, the success of government regulations for restraining a pandemic is vastly influenced by the social responses and individual practices. Multiple strategies improve the reliability of disease transmission barriers.

Non-pharmaceutical interventions also play crucial roles in allocating acute and critical care beds. Fig. 11 shows the estimation of the availability of acute and critical care beds during a pandemic.

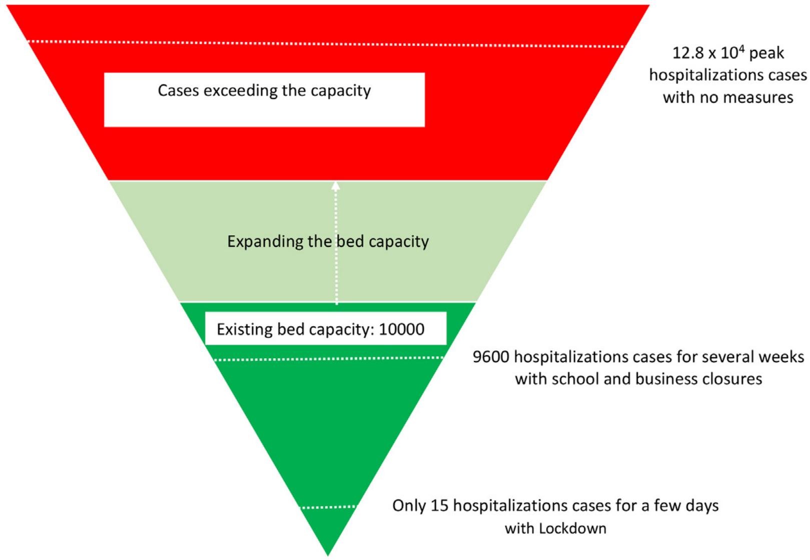

Fig. 14. The outcome for the ALARP based implementation for the risk management in COVID-19.

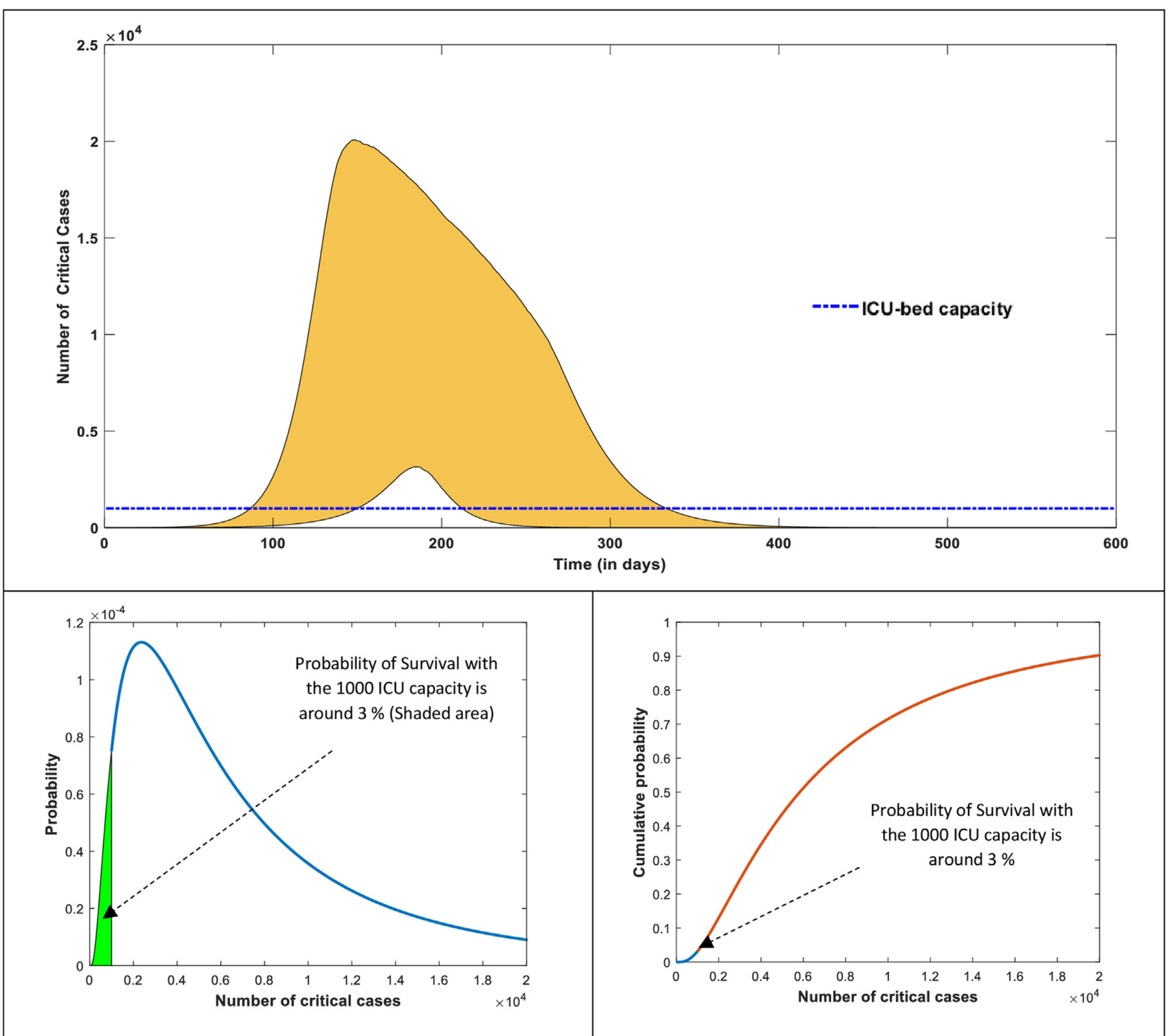

Fig. 15. Reliability analysis with the existing healthcare facilities with **no measures** enforced to restrict the COVID-19 pandemic.

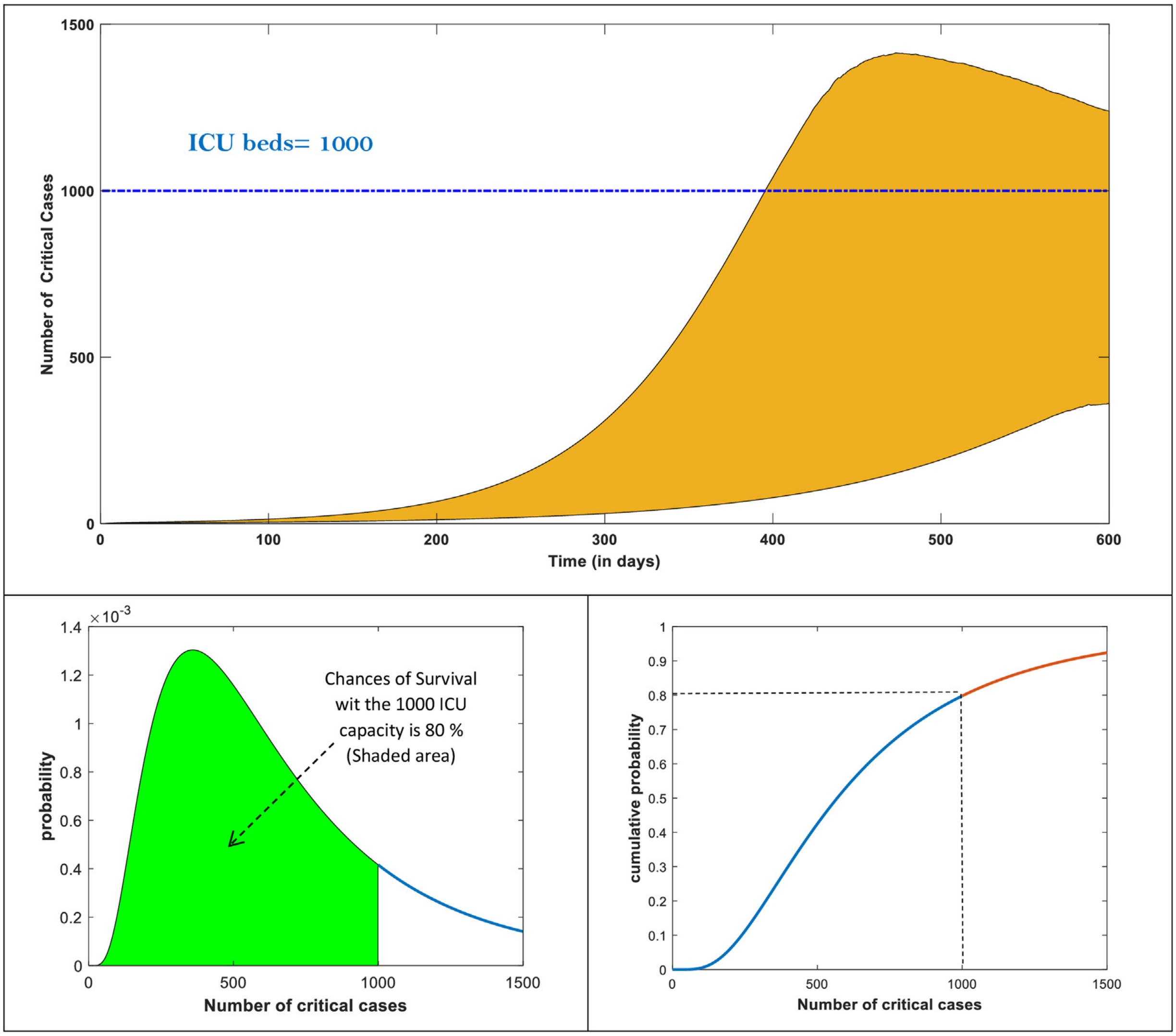

Fig. 16. Reliability analysis with the existing healthcare facilities with **School/business closures** enforced to restrict the COVID-19 pandemic.

The vulnerability of infected individuals rely on their health history and the availability of sophisticated treatment, which depends upon the following factors-

1 The capacity of the healthcare system
2 The stage at which a person is getting infected. This is because the existing beds might be occupied by other patients if the person is being infected at a relatively mature stage of the outbreak.
3 The intervention(s) enforced

The temporal variation of the hospitalization status and the new cases due to the COVID-19 pandemic under distinct regulations (i.e. no measures, school and business closures, and lockdown) has been presented in Fig. 12. We have assumed that 25 % of the infected persons are home quarantined. We can observe that the healthcare systems would be exhausted quickly if no measures were taken (Fig. 12A). However, the existing healthcare system would suffice under the schools and business closures (Fig. 12B) and lockdown (Fig. 12C). Tables 3 and 4, respectively, present the consequences if someone is infected at **T = 200th** and **T = 550th** day since the outbreak. We have assumed that Ontario's initial health care system has 10000 acute care beds for COVID patients, with **1000** beds available for critical and intensive care (Barrett et al., 2020). However, Ontario's government has been significantly expanding the healthcare capacity in preparation for the COVID-19 outbreak.

A simplified event tree diagram for the risk when infected on the 200th day is presented in Fig. 13. Here, natural healing, acute care, and intensive care are the barriers against fatality due to COVID-19. The success of a barrier represents the availability of the barrier and successful recovery resulting from the treatment. The facilities' allocation depends on the healthcare capacity, the enforced intervention, and the stage at which one has got infected, as discussed earlier. The probability of the bed allocation on the 200th day of the outbreak is scant that results in a high likelihood of fatality if no measures are taken. However, the bed allocation probability is virtually 1 (i.e., guaranteed bed allocation) with a 97 % probability of safe recovery if restrictive school and business closure measures or the lockdown are enforced. The risk of fatality has been calculated assuming a 90 % recovery rate of the acute care and 70 % recovery of critical care systems. The admission and recovery rate of intensive care is a complex function of many factors, including age, gender, geography, treatment, and comorbidities, i.e., the overlap of multiple medical conditions. That might be a reason for the lack of consensus in reporting the proportion of ICU admissions. Abate et al. (2020) reported the rate of ICU admissions of 32 % (95 % CI: 26–38, 37 studies and 32, 741 participants). The other commonly reported values of ICU admission include 5% (Guan et al.,

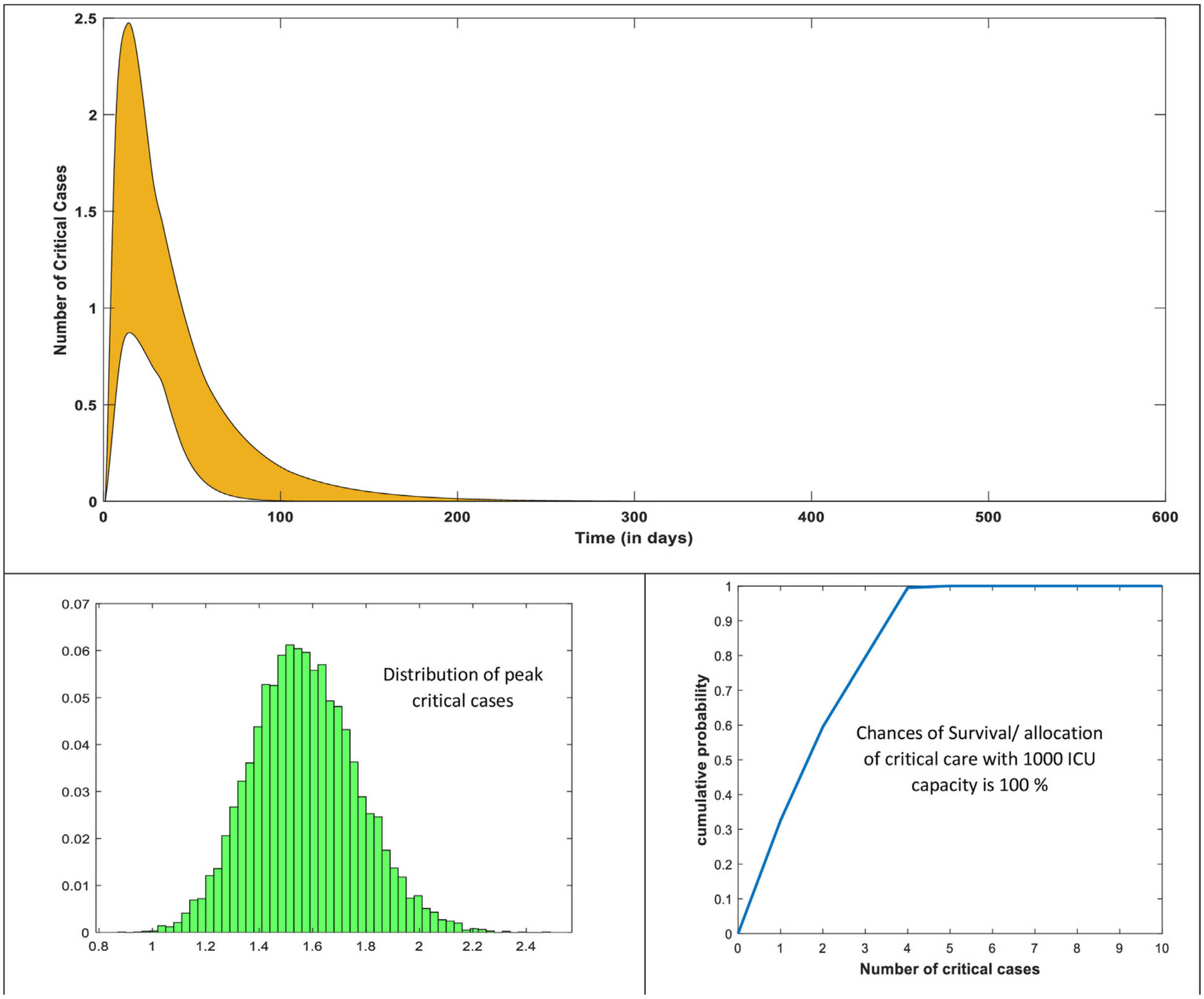

Fig. 17. Reliability analysis with the existing healthcare facilities with lockdown to restrict COVID-19.

Table 3
Risk to the infected person if infection at the 200th day of the outbreak with an acute care bed capacity of 10000 and ICU bed capacity with ventilators of 1000.

Assuming a 90 % recovery rate of acute care and 70 % recovery rate of critical care systems
a *If no measures enforced*:
New cases requiring acute care = 19170
Occupied bed/ (old cases)= 116917 (exceeding bed capacity)
Probability of allocation of bed = 0
Probability of safe recovery= 0.00*x*.90 + 0.00*x* 0.10x0.00x0.70 = 0.00
Probability of death due to unavailaibility of acute and critical cares = 1 − Probability of safe recovery =1 − 0.00 = 1
b *School and business closures:*
New cases seeking acute care (based on the most probable value) = 47
Occupied bed/ (old cases)= 255
Available beds for allocation=10000−255=9745
Probability of allocation of bed =1
Probability of safe recovery= 1*x*.90 + 1.00*x* 0.10*x*1.00*x*0.70 = 0.97
Probability of death due to unavailaibility of acute and critical cares= 1 − Probability of safe recovery = 1 − 0.97 = 0.03
c *Lockdown:*
New cases (based on the most probable value) = 0
Occupied bed/ (old cases)= 0
Available beds for allocation=10000-0=10000
Probability of allocation of bed = 1
Probability of safe recovery= 1*x*.90 + 1.00*x* 0.10*x*1.00*x*0.70 = 0.97
Probability of death=1 − Probability of safe recovery = 1 − 0.97 = 0.03

Table 4
Risk to the infected person when infection at T = 550 with ICU bed capacity of 1000 under distinct regulations.

	No measures	School and business closures	Lockdown
New cases (based on the most probable value)	0	1652	0
Occupied bed/ (old cases)	0	9235	0
Probability of allocation of bed	1	$\frac{10000-9235}{1652}$=0.46	1
Probability of safe recovery	1	$0.46x\ .90 + 0.46x0.1x\ 0.70 = 0.45$	1
Probability of Death	0	0.55	0

2020), 16 % (Grasselli et al., 2020), and 20 % (Baker et al., 2020) of all hospitalized patients.

An early report from China stated a mortality rate of 80 % in ICU; however, this mortality rate dropped to one-third and improving over time (Abate et al., 2020; Launey et al., 2020). We have assumed a 10 % admission rate to ICU and 30 % mortality rate of intensive care units in our calculations. We have not quantified the recovery from natural healing due to data unavailability in this regard.

3.3. Risk analysing using ALARP

The ALARP principle states that risk-reducing measures should be implemented, provided that the costs are not grossly disproportionate to the benefits earned (Pike et al., 2020). We have assumed that the stricter the regulation, the higher will be the economic infliction.

Fig. 14 shows the ALARP representation of the tolerable risk of the COVID-19 pandemic for Ontario. The approach sets an upper limit above which the risk must be reduced and a lower limit below which the spent resources yield a marginal reduction in the fatality risk. The region could be divided into acceptable, tolerable, or unacceptable where the cases surpass healthcare capacity. With no intervention, the healthcare would not suffice the 12.8×10^4 new cases on the 187th day of the pandemic. The fatality risk could be minimized either by extending the healthcare capacity or by enforcing interventions. The model predicts 9600 hospitalization cases for several weeks with school and business closures. This number drastically reduces to 15 hospitalization cases for a few days with the lockdown. Imposing interventions and expanding the healthcare capacity would be a practical approach to addressing a pandemic.

3.4. Reliability/ Survival analysis with the existing healthcare systems

The worst possible outcome of the disease for an infected individual would be death. The infected people could be recovered if they avail of the sophisticated treatment. Healthcare accessibility depends upon the healthcare system's capacity, the stage of the outbreak at which one is infected, and imposed intervention(s) (Section 3.2).

Figs. 15–17 present the survival analysis for the COVID-19 pandemic with the existing healthcare facilities (critical care beds: 1000) under distinct scenarios with no measures, schools and business closures, and lockdown. The survival estimates are based on the Monte Carlo simulation to capture uncertainties in the number of infection cases due to randomness in the incubation, infection, and recovery periods. This is represented by the area under the probability distribution of the cases requiring critical-care on a given day. Similarly, it is also represented by the value of the cumulative probability distribution of the cases requiring critical-care. These survival computations are based on the accessibility of critical care; the true values would be lower because of the fractional recovery rate (less than 100 %) of the treatment.

The most probable estimates indicate that the treatment is not accessible to infected individuals for most of the peak durations if no measures are enforced (Fig. 15). The survival ability under the existing healthcare system would be negligible in this case. The corresponding survival ability values for the schools and business closures and lockdown with the existing capacity are 80 % (Fig. 16) and 100 % (Fig. 17). Thus, these measures are forceful in minimizing the fatality risk in the COVID-19 pandemic.

4. Conclusions

This work explores the risk management of a pandemic using engineering safety approaches. The pandemic risk management approaches have been categorized into distinct hierarchical risk reduction strategies: inherent, active, passive, and procedural. We have highlighted how passive control strategies could help mitigate the present and future infectious diseases' risk. The impact of the epidemic on an infected individual and the community under distinct scenarios was outlined. We have also developed an event tree diagram for pandemic risk management under assorted barriers such as natural evolution, government interventions, societal responses and individual practices. Finally, an infected individual's survival with the existing healthcare systems has been investigated under different intervention strategies.

The risk analysis in terms of the number of infections and mortality was performed using precautionary and as low as reasonably practicable principles. We have included the notion of probability to account for the disease's random impacts using Pate-Cornel's six levels of analyses. The risk calculations were carried out using a semi-mechanistic SEIQRD model along with the Monte Carlo simulations. The results show that the implementation of non-pharmaceutical interventions has a profound effect on reducing the risk. The case study demonstrated that the PP and ALARP are applicable in the pandemic-containment decision-making process.

This work does not take into account other fatalities arising from the interruption in health services for chronic disease. Many surveys highlighted the partial or complete disruption of healthcare for hypertension, diabetes-related complications, cancer treatment, and cardiovascular emergencies due to imposed regulations in the COVID-19 pandemic. Moreover, the present work does not capture the vulnerability factor in the analyses, which could be addressed in future works. The model could also be improved by dividing populations based on demographics, spatial dispersion, and interaction patterns. Rapid testing, contact tracing, and isolation which are critical to controlling disease transmission could also be incorporated for potential improvement.

The test models illustrate the effectiveness of distinct strategies in containing a pandemic with minimal fatality. Lockdown was the most effective measure for reducing risk, but we have no credible estimate of how much reduction came from voluntary isolation and social distancing. This supports many analyst's claims of saving lives using lockdowns. However, we are not advocating for the strict lockdown as its devastating impacts on the economy and mental health cannot be undermined. The stringent lockdown and prolonged confinement can cause neuropsychiatric problems, psychological disorders, and weakened immune systems. A holistic approach with strong ethical and sensible measures is required for combating the epidemic spread (Institute of Medicine, 2007). We have to be prompt in all facets of the transmission; adequate testing facilities, active surveillance, enforcing intervention strategies, and community screening around the cluster areas. Many researchers advocated for "smarter lockdowns" based on granular epidemiological data, temporal segregation, and the social bubble model that allows interaction within a defined group of people while adhering to physical distancing rules with those outside that group (Dhillon and Karan, 2020, & Greg Ip, 2020). The extensive support and public endorsement can be asserted by effectively communicating the preparedness and response strategies. The migration and other cross-border entries pose the risk of further spreading an outbreak; it must be handled effectively (Mowat and Raafi, 2020; WHO, 2018).

The real risk of a pandemic is difficult to assess due to uncertainty in several aspects such as the mechanism of COVID-19 transmission, uncertainty in the R-value, randomness in incubation, infection, and recovery period. Nonetheless, the risk could be minimized by adopting evidence-based holistic approaches with clear ethical and rational measures such as adequate testing facilities, active surveillance, enforcing intervention strategies, community screening around the cluster areas.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgment

The authors thankfully acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada through the Alliance Grant and the Canada Research Chair (Tier I) Program in Offshore Safety and Risk Engineering.

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